Clinical Assessment of the Deep Cervical Flexor Muscles: The Craniocervical Flexion Test

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Abstract

Background: The craniocervical flexion test (CCFT) is a clinical test of the anatomical action of the deep cervical flexor muscles, the longus capitis, and colli. It has evolved over 15 years as both a clinical and research tool and was devised in response to research indicating the importance of the deep cervical flexors in support of the cervical lordosis and motion segments and clinical observations of their impairment with neck pain.

Special Features: The CCFT could be described as a test of neuromotor control. The features assessed are the activation and isometric endurance of the deep cervical flexors as well as their interaction with the superficial cervical flexors during the performance of five progressive stages of increasing craniocervical flexion range of motion. It is a low-load test performed in the supine position with the patient guided to each stage by feedback from a pressure sensor placed behind the neck. While the test in the clinical setting provides only an indirect measure of performance, the construct validity of the CCFT has been verified in a laboratory setting by direct measurement of deep and superficial flexor muscle activity.

Summary: Research has established that patients with neck pain disorders, compared to controls, have an altered neuromotor control strategy during craniocervical flexion characterized by reduced activity in the deep cervical flexors and increased activity in the superficial flexors usually accompanied by altered movement strategies. Furthermore, they display reduced isometric endurance of the deep cervical flexor muscles. The muscle impairment identified with the CCFT appears to be generic to neck pain disorders of various etiologies. These observations prompted the use of the craniocervical flexion action for retraining the deep cervical flexor muscles within a motor relearning program for neck pain patients, which has shown positive therapeutic benefits when tested in clinical trials. (J Manipulative Physiol Ther 2008;31:525-533)

Key Indexing Terms: *Neck Muscles; Neck Pain; Assessment; Exercise; Outcome Assessment (Health Care); Spine; Cervical Vertebrae*

From a historical perspective, the craniocervical flexion test (CCFT) has evolved over some 15 years. It was originally developed in response to interest in the functional roles of muscles particularly in relation to active spinal segmental stabilization and the clinical need for more directed and specific therapeutic exercise for patients with neck pain disorders. Although all muscles contribute to the support of the spine in a complex and intricate way, research into low back pain at the time was indicating that patients with back pain disorders exhibited particular impairments that altered the morphology and motor control of the trunk muscles and particularly of the deep trunk and spinal muscles that appeared detrimental to their function in spinal segmental support and control.[1,2] This encouraged us to view assessment of the neck muscle system from a perspective that was different to conventional testing of strength and endurance of muscle groups, with an aim to test the deep cervical muscles more selectively. The deep cervical flexors (longus capitis and colli) captured our interest in the first instance, prompted both by the clinical teachings of Janda[3] who observed regular impairment of these muscles in patients with neck pain disorders and by the functional anatomical research that was confirming their importance in support of the cervical lordosis and motion segments.[4-10]

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The early development of the CCFT was for the purpose of clinical application and was based on several principles. Previous clinical tests of the deep cervical flexors involved either the performance of a maximum voluntary contraction,[11] or a test whereby cervical flexors were engaged en-mass by maintaining a flexed orientation of the craniocervical region during a head lift against gravity.[12,13] Such higher load tests do not allow ready clinical differentiation between activation of deep and superficial cervical flexors and do not reflect the deep muscles' functional requirements in sustaining low-intensity contractions to support the cervical joints in many functional activities which require prolonged postures and repetitive movements.[4,14] A different method was required to better target the longus capitis and colli. We adopted the general principle of muscle testing by using these muscles' primary anatomical action, flexing the head on a stable cervical spine. This permitted some specificity, as craniocervical flexion is the primary action of the longus capitis muscle that attaches to the cranium and the superior portion of the longus colli that attaches to the first cervical vertebrae. In contrast it is not the primary action of the sternocleidomastoid (SCM) muscles which have extensor moments at the craniocervical region or of the anterior scalene (AS) muscles which have no attachment to the cranium. The CCFT comprised a precise and controlled performance and maintenance of positions of craniocervical flexion in a supine position. There was no element of head lift, which would encourage action of the superficial flexors. The test was deliberately low-load to reflect the function of the deep flexors in active movements and postures. There was a need for quantification of the muscles' performance in the CCFT in the clinical setting. The muscles are deep, any contraction cannot be seen, and manual resistance, which could grade a contraction, was not desirable as it would necessarily recruit required synergists to resist the force. A novel indirect method to assist quantification was developed in response to the knowledge that a contraction of the longus colli causes a subtle flattening of the cervical lordosis.[8] The method involved the use of an air-filled pressure sensor (Chattanooga Stabilizer Group Inc., Hixson, TN), which was inserted between the testing surface and the upper neck to monitor the slight flattening of the cervical lordosis associated with the contraction of these deep muscles. Activation of the deep cervical flexors and the pursuant slight flexion of the cervical region are registered as a subtle increase in pressure.

The test was initially used in the clinical setting and observations of the inability of patients with neck pain to perform the test, and the positive clinical response to training the action[15,16] stimulated a program of research both with respect to the test itself and towards a method of specific exercise. This review will describe the CCFT and how it has developed in response to knowledge gained from the clinic and the laboratory. Our research and that of others will be addressed, which has contributed substantial information about the nature of muscle impairment in cervical disorders.

Discussion

The Craniocervical Flexion Test

The CCFT is performed with the patient in supine crook lying with the neck in a neutral position (no pillow) such that the line of the face is horizontal and a line bisecting the neck longitudinally is horizontal to the testing surface. Layers of towel may be placed under the head if necessary to achieve a neutral position. The uninflated pressure sensor is placed behind the neck so that it abuts the occiput and is inflated to a stable baseline pressure of 20 mm Hg, a standard pressure sufficient to fill the space between the testing surface and the neck but not push the neck into a lordosis. The device provides the feedback and direction to the patient to perform the required five stages of the test. The patient is instructed that the test is not one of strength but rather one of precision. The movement is performed gently and slowly as a head nodding action (as if saying "yes"). The CCFT tests the activation and endurance of the deep cervical flexors in progressive inner range positions as the patient attempts to sequentially target five, 2-mm Hg progressive pressure increases from the baseline of 20 mm Hg to a maximum of 30 mm Hg as well as to maintain a isometric contraction at the progressive pressures as an endurance task (Fig 1).

When the test was first described, performance was scored via the pressure level that the patient was able to achieve (activation score) and hold for 10 repetitions of 10-second duration. A performance index was calculated based on the number of times the patient could hold the pressure level achieved for 10 seconds.[17] For example, if a patient could achieve the second level of the test (24 mm Hg) and perform six 10-second holds with the correct action of craniocervical flexion, then their performance index was 4 × 6 = 24. The highest activation score was 10 mm Hg, and highest performance index, 100. Preliminary research on an asymptomatic population aged 18 to 68 years revealed no age or sex effects on test performance and determined a mean activation score of 7.6 ± 2.1 and a performance index of 65.8 ± 27.5, which showed between-day repeatability determined by the Intraclass Correlation Coefficient (ICC = .81 and .93 for the activation score and performance index respectively),[17,18] values which were later replicated by others.[19,20] Of clinical importance, studies of neck pain groups and single case studies using the original clinical test were showing that performance in patients with neck disorders was inferior with mean activation scores in the vicinity of 4 and performance indices of 10.[17,19-24]

Further Research and Development of the CCFT

It was evident that quantifiable measures of muscle activity were required to establish the test's construct

Fig 1. *The clinical application of the craniocervical flexion test. The patient is guided to each progressive pressure increment of the test by feedback from the pressure sensor. The clinician analyses the movement and detects the presence of any activity in the superficial flexors.*

validity, that is, the CCFT tested predominantly and the activation of the deep cervical flexor muscles. In addition, more extensive use of the clinical test led to reflection about how the test was applied in the clinical setting and how patients performed the CCFT. It was observed that neck pain patients used a number of anomalous strategies when asked to attempt to target the 5 progressive pressure levels which included altered movement strategies (eg, more a head retraction action than the action of craniocervical flexion) and excessive use of the superficial flexors. Based on these observations, subsequent research, while not changing the fundamental test, has changed the way the test is conducted and performance is analyzed both in clinical practice and research.

Construct Validity of the CCFT. Electromyography (EMG) was used to determine whether the 5 progressive stages of the craniocervical flexion test reflect progressive activation of the deep cervical flexor muscles in healthy individuals. The challenge was to gain a measure of activity in the longus capitis/colli as the muscles are deep and inaccessible for conventional surface EMG. Two early studies had obtained intramuscular EMG recordings for longus colli on small samples of volunteers,[5,9] but this method has not been used since, probably in respect of risks associated with invasive surgical techniques to the anterior cervical spine.[25] More recently, a novel EMG method was developed, which involved building surface electrodes within a nasopharyngeal suction catheter and suctioning the electrodes onto the posterior pharyngeal wall adjacent to the uvula which is over accessible muscle bulk of the longus capitis and superior portion of the longus colli (Fig 2A).[26] We were able to demonstrate that the greatest EMG amplitude detected with the nasopharyngeal electrode was derived predominantly from these deep cervical flexor muscles and not neighboring jaw and neck muscles.[27] An EMG study seminal to the construct validity of the test[26] showed that in asymptomatic subjects, there was a strong linear relationship between the amplitude of deep cervical flexor muscle activation and the 5 incremental stages of the CCFT (Fig 2B). In contrast, no such relationship was evident for the activity in the superficial cervical flexors (SCM and AS), whose activation only increased significantly in the latter, more challenging phases of the test. Furthermore, the repeatability of normalized EMG amplitude of the deep cervical flexor muscles for the five stages of the CCFT was established as evidenced by low values of the within-subject normalized SEM (range, 6.7%-10.3%).[26]

As previously mentioned, a head lift test with maintenance of the craniocervical flexion position has been used as a test of the deep cervical flexors.[12,28,29] There is no doubt that the deep cervical flexors will be activated in such a task but as shown by Vasavada et al,[30] in a computer model of the head and neck musculoskeletal system, the SCM and AS muscles together provide 83% of the cervical flexion capacity while the longus capitis and colli provide only 17%, suggesting that a cervical flexion/head lift task might not be the best test for specific information about the deep cervical flexors. We compared activity in the SCM, AS, and the deep cervical flexors in performance of cervical flexion (isometric replication of the head lift) and isometric craniocervical flexion using dynamometry methods at maximum voluntary contraction (MVC), 50% and 20% MVC. The results confirmed that tests of cervical flexion result in significantly greater activity of the superficial cervical flexor muscles than tests of craniocervical flexion.[31] Interestingly, there were no differences in normalized EMG amplitude of the deep cervical flexors between the 2 tests at any contraction intensity. Thus, the test of craniocervical flexion may be considered as a more selective test of the deep cervical flexors as compared to conventional cervical flexion tests in which superficial muscle activity may mask impaired performance of the deep cervical flexor muscles (Fig 3). This difference between the 2 testing methods was recently

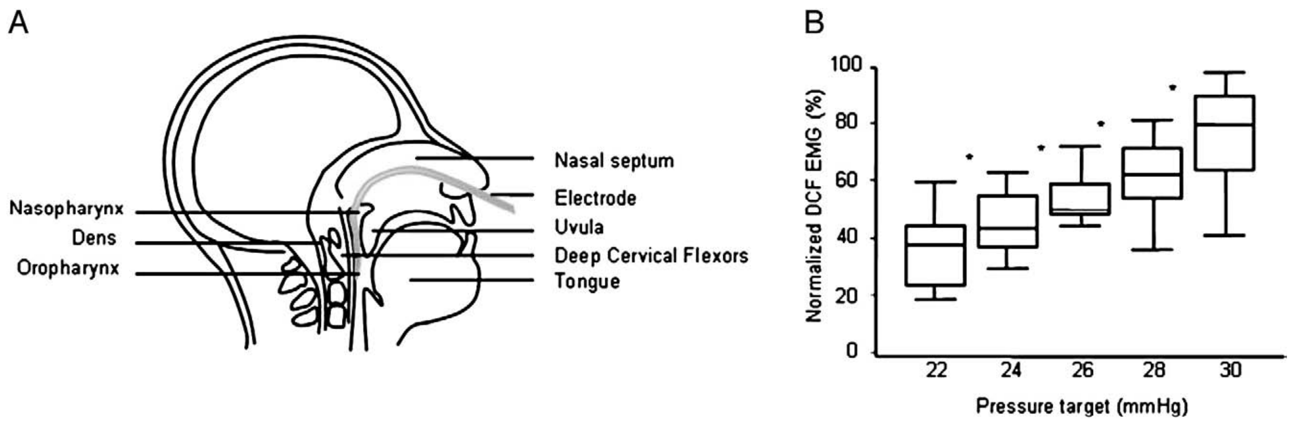

Fig 2. *A, Using a nasopharyngeal application, surface electrodes attached to a suction catheter are positioned over the posterior oropharyngeal wall. The deep cervical flexor muscles lie directly posterior to the oropharyngeal wall, allowing myoelectric signals to be detected from these muscles. B, Plots of normalized root-mean-square values (minimum, 25th quartile, median, 75th quartile, and maximum value) for the DCF muscles across the five stages of the craniocervical flexion test. Analysis of contrasts showed significant differences in EMG amplitude between the successive stages of the craniocervical flexion test. (*P < 0.05). DCF, deep cervical flexor. Reprinted with permission from Phys Ther. 2003;83:899-906.*

confirmed by Cagnie et al[32] in a functional magnetic resonance imaging study.

In respect to the altered movement strategy observed in neck pain patients, a further quantifiable element of the CCFT was the range of craniocervical flexion used in each of the 5 progressive stages of the test. A digital imaging method was used and the angles of craniocervical flexion were recorded at each test stage of the CCFT in an asymptomatic group.[33] Angles were presented as the percentage of full craniocervical flexion range measured in the supine lying position. It was shown that there was a linear relationship between the incremental pressure targets of the CCFT and range of movement used. A mean of 22.9% of full-range craniocervical flexion was used to reach the first pressure target of the CCFT followed by linear increments in subsequent test stages up to 76.6% for the final stage of the test. Excellent inter- (ICC = 0.99) and intrarater reliability (ICC 0.98–0.99) were demonstrated for the angular measurements using this imaging technique, indicating the suitability of this technique to assess of range of motion during the CCFT in future research and in clinical application.[33]

The CCFT and Neck Pain. Electromyography studies were conducted to better understand the properties and responses to the CCFT in neck pain groups and to investigate the clinical observations that patients with neck pain used anomalous strategies in performance of the CCFT. The conditions of the CCFT were changed. Patients were required to attempt all levels of the test rather than cease at the stage they could not hold as per the original test so that a full analysis of performance was obtained. The first EMG study measured activity in the superficial flexors only and revealed that patients with chronic whiplash associated disorders had higher EMG amplitude of the superficial flexor muscles in the test and were less able to control pressure changes than control subjects.[34] Inferences were made that the increased activation of the superficial cervical flexors was likely to be a compensation for reduced deep cervical flexor activation but there was no direct evidence for this assumption. The evidence was provided in a subsequent pivotal study that directly measured activity in the SCM, AS, and deep cervical flexors with the new nasopharyngeal electrode.[35] It was shown that the amplitude of deep cervical flexor EMG was less in the group with neck pain than the control group and was significantly different for the higher increments of the task (Fig 4A). In parallel, there were also strong trends for greater SCM and AS EMG in the neck pain group, indicating altered coordination between the deep and superficial cervical flexor synergy in patients with neck pain. In addition, the neck pain patients were shown to use lesser ranges of craniocervical flexion throughout the test stages.

Several subsequent EMG studies of clinical populations with various neck pain disorders have restricted measurement to activity in the superficial flexor muscles in the CCFT, in deference to the semi invasiveness of the nasopharyngeal electrode.[36-43] They have verified the presence of altered neuromotor control of the cervical flexors with consistent findings of significantly higher activity in the superficial flexor muscles in performance of at least the third to the fifth stages of the CCFT in neck pain, compared to control groups (Fig 4B).

Neck pain patients' inability to sustain isometric contractions in the incremental stages of the clinical CCFT has been demonstrated.[17,20,22,23] The fidelity of this finding was recently demonstrated in a study[44] which used a specially constructed dynamometer (NeckMetrix, University of Queensland, Brisbane, Australia)[45] to measure craniocervical flexor muscle endurance over a range of contraction

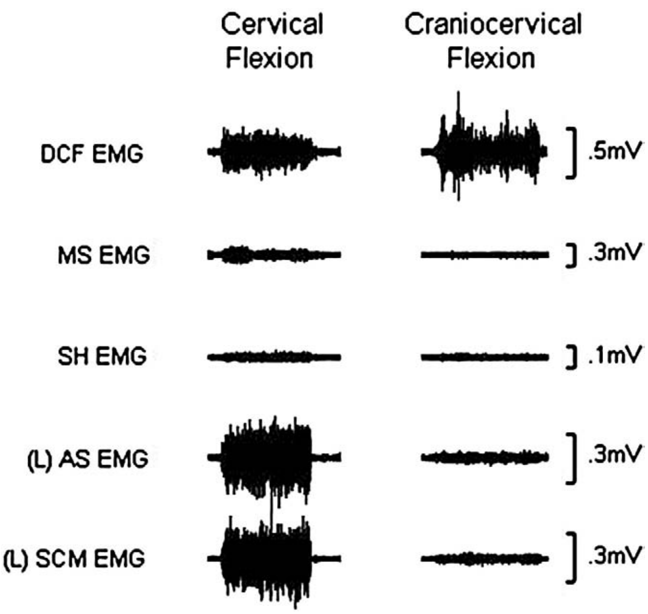

Fig 3. *Raw EMG data for the DCF, MS, SH, and L AS and SCM muscles. Data are shown for a representative healthy control subject during the tasks of cervical flexion and craniocervical flexion. Note that in the task of craniocervical flexion there is minimal activation of more superficial cervical muscles in contrast to the cervical flexion task. MS, masseter; SH, suprahyoid; L, left Reprinted with permission from J Electromyogr Kinesiol. 2006;16:621-628.*

intensities in neck pain sufferers compared to control subjects without neck pain. It was shown that not only did neck pain patients have reduced strength of their craniocervical flexors, but pertinent to the CCFT, they had a significantly reduced capacity to sustain isometric craniocervical flexion at 20% and 50% of MVC. It is the reduced endurance at 20% MVC (or perhaps even lower contraction intensities) that is captured in the CCFT—contraction intensities that are more likely reflective of those used in general daily activities.

Current Clinical Assessment with the CCFT. As a result of the knowledge gained from research, there have been modifications to the CCFT test protocol from its original description, and the test findings now direct rehabilitation strategies more precisely.[46] The current test for the clinical setting is presented in Appendix A. The essential changes are that the clinical test is now performed in 2 stages. The first stage is a visual and palpatory analysis of the movement and activity of the superficial cervical flexor muscles during the five progressive stages of the craniocervical flexion action. The assessment is still to determine which increment of the test the patient can achieve, but importantly, the assessment includes an evaluation of any inappropriate and compensatory movement (eg, retraction) or muscle strategies (eg, excessive use of the superficial cervical flexors). In the presence of an abnormal movement pattern, rehabilitation of the correct pattern takes precedence over further testing at this point, so that endurance of the deep cervical flexors can be tested with some accuracy. If uncorrected, the endurance tests stand to have little meaning. Stage 2 evaluates the number of repetitions at the test stages that the patient is able to achieve while performing and maintaining the correct craniocervical flexion action.

Clinical Status

The CCFT has initiated a journey of discovery into the nature of muscle impairment associated with neck disorders and an exercise method for rehabilitation based on motor relearning principles in the first and intermediate stages of the program.[46] Although this review focuses on the CCFT and the deep cervical flexors, it should not detract from the fact that impairments in cervical flexor and extensor and axioscapular muscle function are proving to be complex and multifaceted, requiring, we contend, specific strategies for rehabilitation.

Nature of Impairments in the Deep Cervical Flexors. Clinical and laboratory studies of the craniocervical flexion action have demonstrated altered activation of the deep cervical flexor muscles both directly and indirectly[39,47] and deficits in their strength and endurance at different contraction intensities.[44] It has also been shown that there are altered temporal characteristics of their activation in people with neck pain via a delay in the timing of the cervical muscles in response to a perturbation induced by rapid arm movement. Rather than responding in a normal feed-forward manner as observed in pain-free individuals,[48,49] the onsets of the cervical flexors and to the greatest extent, the deep cervical flexors is delayed.[50] This provides further evidence for a change in motor control with neck pain and a potential compromise in the cervical spine's control which may leave it vulnerable to further strain.

A Generic Impairment in Neck Pain Disorders. Studies using the CCFT indicate that impairment in deep cervical flexor function appears to be generic to neck pain disorders. Similar test results have been gained from different neck pain population groups including: cervicogenic headache,[17,38] whiplash-associated disorders,[40,51] occupationally induced neck pain,[37,52] as well as nonspecific neck pain groups.[35,42,44] Furthermore, the changes in neuromotor control appear early after the onset of the disorder as was in evidence in a study of persons with acute whiplash, measured within 4 weeks of injury.[41] It is likely, from clinical observation, that the deep cervical flexors demonstrate changes even sooner after the onset of pain or injury as has been documented for the lumbar multifidus,[1] although this needs to be substantiated.

Deep Cervical Flexor Impairment and Differential Diagnosis. There can be challenges in differential diagnosis of the 3 common intermittent frequent headache forms of migraine without aura, tension-type headache, and cervicogenic headache

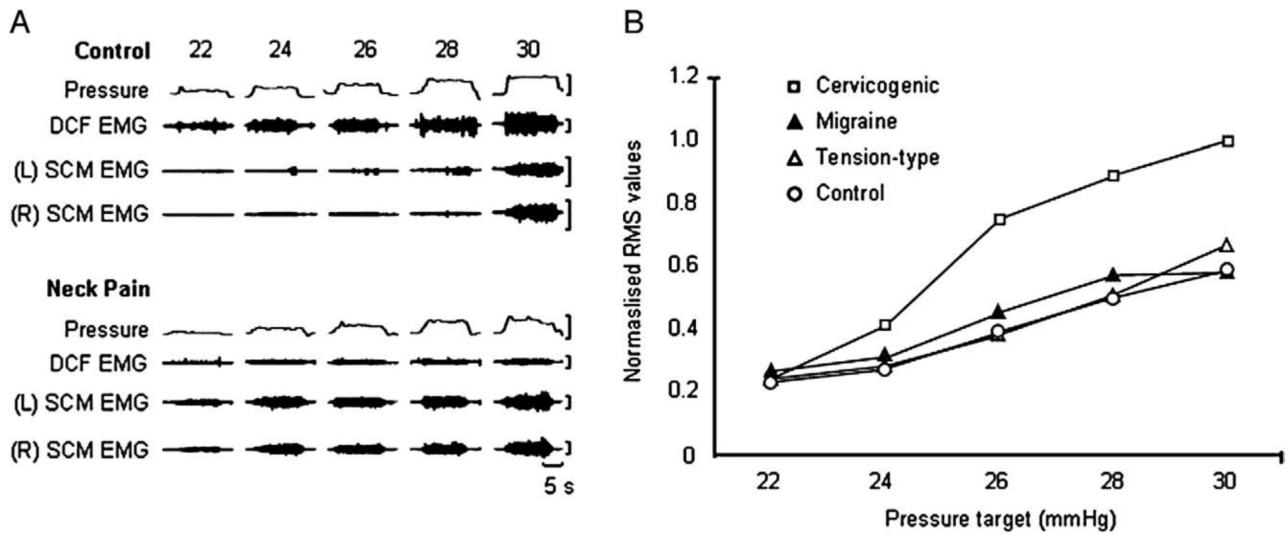

Fig 4. *A, Representative raw EMG data are shown for a control subject and person with neck pain during a task of staged craniocervical flexion. Data are shown for the DCFs and L and R SCM muscles. Note the incremental increase in EMG activity for all muscles with increasing craniocervical flexion but with lesser activity in the deep cervical flexors and greater activity in the superficial muscles for the neck pain patient suggesting a reorganization of muscle activity to perform the task. EMG calibration: 0.5 mV. R, right. Reprinted with permission from Spine 2004;29:2108-2114. B, Patients with cervicogenic headache display increased EMG activity (expressed as RMS) of the sternocleiodmastoid muscle during the craniocervical flexion test compared to control subjects. Note that no differences were observed between people with migraine or tension-type headache compared to controls. RMS, root mean square. Redrawn with permission from Cephalalgia 2007;27:793-802.*

because of symptomatic overlap. In a recent study assessing the usefulness of measures of cervical musculoskeletal impairment in differential diagnosis, we were able to show that the concurrent presence of reduced range of movement, impaired activation of the deep cervical flexor muscles (CCFT), and the presence of palpable upper cervical symptomatic joint dysfunction differentiated subjects with cervicogenic headache from migraine, tension-type headache, and control subjects with 100% sensitivity and 94% specificity.[38] The combined presence of this joint and muscle dysfunction could also depict cervicogenic headache as one of one or more headaches reported by subjects with multiple headache.[36] Similar findings were reported by Zito et al.[43] It must be emphasized that it was the combination of impairments that was diagnostic of cervicogenic headache, rather than isolated measures of either the CCFT or range of movement.

Specific Rehabilitation to Change the Impairment. Research into muscle dysfunction in neck pain disorders, which stimulated the development of the CCFT, also directed the development of a specific exercise approach focusing on rehabilitation of muscle control of the cervical and axioscapular muscles.[46] The program, inclusive of training the craniocervical flexors, has proven to be effective either prescribed alone or within a multimodal context.[22,40] New knowledge has been generated in these and other clinical studies using the CCFT. For example, evidence from a prospective study of whiplash and a clinical trial of treatment of cervicogenic headache indicated that there is not automatic recovery of impaired neuromotor control, detected in the CCFT, even with resolution of the neck pain.[22,51] Specific training appears to be required. Furthermore, outcomes from clinical trials and case studies indicate that the CCFT can detect improvements gained from training the craniocervical flexors.[22,40] Studies have shown that specific training of the craniocervical flexor muscles is effective at increasing the activation of the deep cervical flexor muscles[40] and improving the ability to maintain an upright posture of the cervical spine during prolonged sitting.[53]

Conclusion

The CCFT evolved from a dual interest in understanding the nature of impairments associated with cervical musculoskeletal disorders and developing appropriate exercise interventions for neck pain patients. Further research is required in both spheres of interest. The psychometric properties of the CCFT require further dedicated research and indeed we need to know more about the physiological properties encompassed in the performance and outcomes of the test. Recent research suggests that the CCFT might incorporate more kinesthetic elements than first appreciated[54] and the effect of natural breathing patterns on test performance has recently been revealed.[55] Research is ongoing to further our understanding of muscle impairments in neck pain disorders and to translate such information into appropriate tests for the clinical setting and research on informed therapeutic exercise programs.

Practical Applications

- The craniocervical test is a clinical test of deep cervical flexor muscle function.
- The strategy to perform upper cervical flexion is analyzed and isometric endurance assessed.
- Neck pain patients demonstrate altered neuromotor control characterized by impaired activation of the deep cervical flexor muscles.
- This impairment appears generic to neck pain disorders.
- Training the deep cervical flexor muscles has shown to be effective at reducing neck pain symptoms.

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Appendix A. The clinical protocol for the craniocervical flexion test

Indications: patients with neck pain disorders; acute, subacute and chronic presentations.

Contraindications: the test is performed in supine lying and is equivalent to the function of nodding to say "yes." Thus, there are few contraindications to its application. The presence of neural tissue mechanosensitivity causing pain with movement of craniocervical flexion would delay the test in its current format until this sensitivity has resolved. The CCFT should not produce head or neck pain.

Stage 1: Analysis of performance of the craniocervical flexion action.

The patient is positioned in supine, crook lying with the pressure biofeedback in situ and is given the dial to guide performance of the test (Fig 1). They are requested to slowly feel the back of their head slide up the bed in a head nod action to elevate the target pressure from 20 to 22 mm Hg and to hold the position for two or three seconds before relaxing and returning to their starting position. If subjects have an apical breathing pattern, the nod should be performed on exhalation.[55] This process is repeated through each 2-mm Hg increment of the test to 30 mmHg.

The clinician analyses the motion of the head and the muscle activity in the superficial flexors by observation or palpation. The motion should be a head rotation of progressively increasing range through the five stages of the test,[33] and there should be negligible activity palpated or observed in the SCM or AS muscles until the last 1 or 2 stages of the test, if at all. Signs of abnormal patterns or poor activation of the deep cervical flexors include the following: the range of head rotation does not increase with progressive increments of the test and the movement strategy becomes more a head retraction action; the patient lifts the head in attempts to reach the target pressures; the movement is performed with speed; there is palpable activity in the superficial flexor or hyoid muscles in the first three stages of the test; the pressure dial does not return to the starting position, and reads a pressure greater than 20 mm Hg, indicating an inability to relax the muscles after a contraction—an inability to relax the scalenes is often palpated with this occurrence.

The baseline assessment: the stage of the test (increment of pressure increase) that the patient can achieve and hold for 2 to 3 seconds with the correct craniocervical flexion action, without palpable activity of the superficial flexors provides quantification of performance in this stage of the test.

Stage 2: Testing isometric endurance of the deep cervical flexors at test stages that the patient is able to achieve with the correct craniocervical flexion action.

This stage is conducted when the patient can perform the correct craniocervical flexion action, even if they cannot reach all target pressures. It is delayed when substitution movements (eg, head retraction) are observed in stage 1 of the test.

The patient performs the head nod action to first target the lowest level (22 mm Hg) and holds the position for 10 seconds. In assessment, if the patient can perform at least 3 repetitions of 10-second holds without substitution strategies, the test is progressed to the next pressure target.

The clinician continues to observe the movement strategy that the patient uses to ensure that it remains a craniocervical rotation. Signs of reduced endurance at the test increment include the following: the patient cannot hold the pressure steady and it decreases (although they seem to be holding the head in the flexed position); the superficial flexors are overtly recruited; and the pressure level is held but it is with a jerky action, suggesting an alternate muscle is being sought by the patient to hold the pressure level, and most likely indicates weakness or fatigue of the deep cervical flexors.

The baseline assessment is documented as the pressure level that the patient can hold steady for repeated 10-second holds, with minimal superficial muscle activity and in the absence of any other substitution strategies.